Propagation Mechanism of Long-Period Ground Motions for Offshore Earthquakes along the Nankai Trough: Effects of the Accretionary Wedge

by Yujia Guo, Kazuki Koketsu, and Hiroe Miyake

Abstract A thick accretionary wedge with low seismic velocity overlying a subducting plate is an important factor affecting the amplitudes and durations of long-period ground motions for great offshore earthquakes. We performed a series of 3D long-period ground-motion simulations to obtain a better understanding of the effects of the accretionary wedge along the Nankai trough, Japan. The simulation results demonstrate that the accretionary wedge has the effect of decreasing the peak amplitude and velocity response but amplifying and elongating later phases of long-period ground motions in the land area. These effects depend significantly on the focal depth and are pronounced for shallow seismic sources. The amplified and elongated later phases originate mainly from prominent basin-induced surface waves excited near the trough axis. We also identified hard sediments with intermediate S-wave velocity in the accretionary wedge as a key layer that enhances the propagation of long-period ground motions from offshore to onshore. In the case of the Nankai trough, the hard sediments allow long-period ground motions developed inside the accretionary wedge to be efficiently transmitted outward in the longer period than ∼10 s. Comparisons between the observed and simulated records suggest that for more accurate predictions of long-period ground motions, velocity structure models of not only the accretionary wedge but also the surrounding upper crust should be validated and revised using seafloor observations.

Introduction

Great subduction earthquakes have the potential to generate long-period ground motions efficiently. Because of weak attenuation, propagation path, and site amplification effects in distant sedimentary basins, long-period ground motions are often observed with large amplitudes and long durations. These ground motions cause serious damage to large-scale structures such as high-rise buildings, oil storage tanks, and suspension bridges in metropolitan areas. The worst disaster related to long-period ground motions was caused by the 1985 Michoacan earthquake (MW 8.0) along the Middle America trench. This earthquake killed about 20,000 people and demolished many buildings in Mexico City, at a distance of 400 km from the source region (Anderson et al., 1986; Beck and Hall, 1986). In Japan, destructive long-period ground motions during the 2003 Tokachi-oki earthquake (MW 8.3) along the Kuril trench triggered fluid sloshing and subsequent fires in oil storage tanks in the Yufutsu basin away from the source region (e.g., Koketsu et al., 2005). Moreover, Santiago, Chile, also suffered damage to high-rise buildings (e.g., Naeim et al., 2011) from long-period ground motions during the 2010 Maule earthquake (MW 8.8) along the Peru–Chile trench; the ground motions were observed to have large peak ground displacement and long duration (Boroschek et al., 2012; Liberatore et al., 2012). For future subduction earthquakes, several studies have highlighted the importance of long-period ground motions from simulations of scenario earthquakes (e.g., Olsen et al., 2008; Maeda et al., 2013; Delorey et al., 2014; Pulido et al., 2015).

Subduction earthquakes along the Nankai trough, off southwest Japan, are also capable of exciting significant long-period ground motions in distant and deep sedimentary basins such as the Osaka, Nobi, and Kanto basins (Fig. 1) beneath the Osaka, Nagoya, and Tokyo metropolitan areas, respectively. Great subduction earthquakes along the Nankai trough have occurred repeatedly with a recurrence interval of 100–200 years (Ando, 1975). The most recent events, with moment magnitudes larger than 8, occurred in 1944 and 1946 in the Tonankai and Nankai regions, respectively (Fig. 1). However, the Tokai region has not experienced a great earthquake since the 1854 event. The occurrence potential of the forthcoming subduction earthquake along the Nankai trough was estimated to be 60%–70% within 30 years of 1 January 2013 (Headquarters for Earthquake Research Promotion, 2013).
Along the Nankai trough, a very thick and low-velocity accretionary wedge overlies the subducting Philippine Sea plate (e.g., Nakanishi et al., 1998). Furumura et al. (2008) performed numerical simulations of long-period ground motions during the 1944 Tonankai earthquake ($M_w 8.1$) and the 2004 off the Kii Peninsula intraplate earthquake ($M_w 7.5$), and pointed out that the accretionary wedge has an important path effect in terms of guiding long-period surface waves toward the Kanto basin. This guidance effect was also confirmed by Ikegami et al. (2008). These studies imply that the accretionary wedge has the potential to affect the propagation mechanism of long-period ground motions for great earthquakes along the Nankai trough, whereas site amplification effects within a sedimentary basin are predominant for long-period ground motions arising from great earthquakes along other subduction zones.

To examine accretionary wedge effects on long-period ground motions, Yamada and Iwata (2005) and Yoshimura et al. (2008) performed long-period ground-motion simulations at several rock sites in the vicinity of the accretionary wedge during the largest foreshock ($M_w 7.2$) of the 2004 off the Kii Peninsula intraplate earthquake, and concluded that the accretionary wedge decreases the peak amplitude and prolongs the duration of later phases. Although these were pioneering studies in terms of clarifying the effects of the accretionary wedge along the Nankai trough on long-period ground motions, there were few insights into the propagation mechanism from the offshore to onshore area, which is necessary to provide an appropriate explanation for effects.

More recently, Watanabe et al. (2014) produced a detailed description of the performance of long-period ground motions from the accretionary wedge to the Kanto basin. Their discussion was mainly limited to long-period ground motions within a period range of 3–5 s, although long-period ground motions in the Kanto basin are characterized by seismic waves >7 s (e.g., Hayakawa et al., 2005; Miyake and Koketsu, 2005). Petukhin et al. (2016) also suggested that surface waves generated in the accretionary wedge cause the time delay and longer duration of long-period ground motions in the Osaka basin.

In most cases, the velocity structure models constructed and used for long-period ground-motion simulations include a larger degree of uncertainty in the offshore area than in the onshore area, primarily due to insufficient seismic surveys and information about the S-wave velocity, which has a key influence on seismic waves. For the Nankai trough, few studies have measured Poisson’s ratios or S-wave velocities in the accretionary wedge except for the western end of the trough (Takahashi et al., 2002) and part of the Tonankai region (e.g., Tsuji et al., 2011). Furthermore, as subduction earthquakes along the Nankai trough occur in spatially diverse source regions, accretionary wedge effects are likely to be governed by the source location. Therefore, accretionary wedge effects should be evaluated with respect to the choice of the source location as well as seismic velocity. Although Shapiro et al. (2002) simultaneously discussed the effects of the accretionary wedge along the Middle America trench considering these two factors, no such research has yet been conducted for the Nankai trough.

In the present study, we attempt to clarify the propagation mechanism associated with the accretionary wedge and the sensitivities of its effects resulting from differences in velocity structure and source location. To reach our primary goals, we perform a series of long-period ground-motion simulations (Table 1) in which three types of 3D velocity structure models are used: two include the accretionary wedge, each with a different accretionary wedge model, whereas the third model does not incorporate the accretionary wedge. We first simulate the long-period ground motions during the largest foreshock ($M_w 7.2$) of the 2004 off the Kii Peninsula intraplate earthquake. Subsequently, we simulate the long-period ground motions for a virtual finite-source...
model \((M_w 7.4)\) at the plate boundary off the Kii Peninsula, because the largest foreshock was an intraplate rather than an interplate event. We compare the propagation mechanisms of these two events from offshore to onshore. We also discuss the performance of accretionary wedge effects on long-period ground motions in the land area, using simulations for point sources that cover the whole of the accretionary wedge.

**Ground-Motion Simulation Method and Velocity Structure Models**

We used a 3D finite-element method with voxel meshes (Koketsu et al., 2004; Ikegami et al., 2008) for the ground-motion simulations. The finite-element method is well suited for use in a simulation model that incorporates the complex topography, because it satisfies the free-surface condition automatically. Moreover, its combined use with voxel meshes can reduce the required computational time and memory to almost the same level as the finite-difference method (e.g., Grave, 1996). The simulation code implements topography, ocean water, and constant memory to almost the same level as the finite-difference meshes can reduce the required computational time and automatically. Moreover, its combined use with voxel meshes are shown by contours (contour interval: 1000 m). Note that the maps in (b) are rotated by \(\sim 25^\circ\) clockwise. The color version of this figure is available only in the electronic edition.

Figure 2. (a) Thickness of the layer with an S-wave velocity of 1.0 km/s in model A. The distribution of this layer is indicated by contours. The contour interval is 1000 m. The background shows the depth distribution of the top of the layer with an S-wave velocity of 3.2 km/s in the Japan Integrated Velocity Structure Model (JIVSM) (Koketsu et al., 2008, 2012). Distribution maps of model B within the dashed area are illustrated in (b). (b) Thicknesses of layers with S-wave velocities of 0.6, 1.2, and 2.2 km/s in model B. Layer distributions are shown by contours (contour interval: 1000 m). Note that the maps in (b) are rotated by \(\sim 25^\circ\) clockwise. The color version of this figure is available only in the electronic edition.

The simulation code imple-

The finite-element method is well suited for optimizing computational times and memory to almost the same level as the finite-difference method (e.g., Grave, 1996). The simulation code implements topography, ocean water, and constant \(Q_p\) and \(Q_s\) over a wide-frequency range. Discontinuous meshes were also incorporated for optimizing computational times and memories. A nonreflecting boundary condition was employed to eliminate artificially-reflected waves from the side and bottom limits of the simulation models.

Since the 2000s, several 3D unified velocity structure models covering a wide area have been constructed and updated for southern California and Japan (e.g., Kohler et al., 2003; Koketsu et al., 2008, 2012; Shaw et al., 2015). These models provide improved understanding of the propagation of ground motion on a large scale (e.g., Olsen et al., 2006). In Japan, although several seismic surveys have been carried out across the Nankai trough to build a velocity structure model for ground-motion simulations, most of them focused only on the geometry or P-wave velocities of the subduction system. This means that information regarding S-wave velocity, which strongly affects ground motions, is lacking in the offshore area. It is important to take this fact into consideration in investigations of accretionary wedge effects on long-period ground motions. Therefore, our simulations used two types of 3D velocity structure models with different accretionary wedge models. The velocity structure models are composed of homogeneous layers.

Model A was published as the Japan Integrated Velocity Structure Model (JIVSM) by Koketsu et al. (2008, 2012). The JIVSM is one of the most widely utilized velocity structure models for long-period ground-motion simulations in Japan. One of its advantages is that it is calibrated and updated by a forward modeling procedure using observed time-history waveforms (e.g., Iwata et al., 2008; Koketsu et al., 2009; Petukhin et al., 2012; Takemura et al., 2015). In model A, the accretionary wedge has a single layer with an S-wave velocity of 1.0 km/s (Fig. 2a). Model B was compiled on the basis of S-wave velocities estimated by recent studies as follows. Because some seismic surveys (Kodaira et al., 2002; Nakanishi, Takahashi, et al., 2002; Takahashi et al., 2002) suggested that the accretionary wedge contains roughly three layers with different velocities, we divided the wedge into three layers and adjusted the upper depth or thickness of each layer as proposed by Fujiwara et al. (2009, 2012). Next, we defined the S-wave velocities of the three layers as 0.6, 1.2, and 2.2 km/s, respectively, with reference to the Poisson’s ratios estimated by Takahashi et al. (2002), Obana et al. (2009), and Tsuji et al. (2011). Q values for P- and S-waves were determined in the same manner as for the JIVSM. An identical 3D velocity structure model, which was also included in the JIVSM, was
adopted for the outside of the accretionary wedge in models A and B. For the overlapped zone between the accretionary wedge and other structures such as the oceanic crust in model B, a priority was given to other structures. The advantage of model A is that the geometry of the accretionary wedge has been calibrated using observed records. On the other hand, though the accretionary wedge in model B has not been verified against the observed features of long-period ground motions, it more accurately reflects the offshore seismic profiles compared with model A. The spatial distributions of layer thickness in model B (Fig. 2b) show that the layer with an S-wave velocity of 0.6 km/s is thickest in the Tonankai region, where its maximum thickness reaches ∼2000 m. This thick layer corresponds to the Kumano forearc basin, a sediment-filled sea plain. The layer with an S-wave velocity of 1.2 km/s is thickest near the eastern part of the Tonankai region. Moreover, below these two layers, a layer with an S-wave velocity of 2.2 km/s constitutes the major part of the accretionary wedge by volume in model B. In addition to models A and B, we introduced a 3D velocity structure model without the accretionary wedge (model C) by replacing the wedge with a layer that was assigned an S-wave velocity of 3.2 km/s. The physical parameters in the accretionary wedge zone for these models are listed in Table 2, together with those of the Osaka, Nobi, and Kanto basins, as well as several major layers. In these three models, although the lowest S-wave velocity outside the accretionary wedge is 0.35 km/s, corresponding to the top layer in the Osaka and Nobi basins, we replaced this value with 0.5 km/s to ensure stability of the simulations.

### Table 2

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<th>Layer</th>
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<th>Model B</th>
<th>Model C</th>
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<td>5.5</td>
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</tr>
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<tr>
<td>Oceanic crust 3</td>
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### Table 3

Focal Mechanism of the Largest Foreshock of the 2004 off the Kii Peninsula Earthquake

<table>
<thead>
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<th>Parameter</th>
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</tr>
<tr>
<td>Latitude</td>
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<tr>
<td>Focal depth</td>
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<td>Dip</td>
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<tr>
<td>Rake</td>
<td>105°</td>
</tr>
<tr>
<td>Seismic moment</td>
<td>6.96 × 10^19 N·m (Mw 7.2)</td>
</tr>
</tbody>
</table>

The Largest Foreshock of the 2004 off the Kii Peninsula Earthquake

The largest foreshock occurred 100 km or more away from the Kii Peninsula (Figs. 1 and 3a) at 10:07 a.m. on 5 September 2004 (UTC), preceding the mainshock (Mw 7.5) that took place nearly five hours later. The Japan Meteorological Agency estimated the source depth of the largest foreshock to be 38 km. Because the largest foreshock occurred with a simpler rupture pattern, for which the main slip was estimated only near the hypocenter (e.g., Yagi, 2004; Park and Mori, 2005; Bai et al., 2007), we selected the largest foreshock as the target event. We assumed a point source (Table 3) and source time function (Fig. 3b) on the basis of the source process analysis by Yagi (2004). The focal depth was 18 km, which corresponds to the depth of the oceanic mantle in the velocity structure models. Our simulation model covered an area of...
Figure 3. (a) The simulation area for the largest foreshock of the 2004 off the Kii Peninsula earthquake. Rectangular area represents the simulation area. Triangles denote K-NET and KiK-net stations. The velocity waveforms at these stations are illustrated in Figure 4. Star marks the epicenter. Contours indicate the distribution of the total thickness of the accretionary wedge in models A and B. The contour interval is 1000 m. (b) Time history of the source time function during the largest foreshock.

514 km × 270 km (Fig. 3a) and extended to a depth of 69 km and an altitude of 1.8 km, including the Osaka, Nobi, and Kanto basins. The volume was discretized using cubic meshes with side lengths of 350 m for the major part, and 175 m for depths from sea level shallower than 7 km to satisfy the Courant condition for the lowest S-wave velocity. We simulated velocity waveforms lasting for 400 s from the earthquake origin time and applied a band-pass filter at 0.05–0.3 Hz.

Amplified and Elongated Later Phases at Land Stations

In the first step, we compared the simulated waveforms with the observed ones at several K-NET and KiK-net (Aoi et al., 2011) land stations, as illustrated in Figure 4. Figure 5 shows the velocity response spectra with a damping factor of 5%, which are the peak amplitudes of velocity motions of single-degree-of-freedom systems with various natural frequencies responding to seismic ground motion (e.g., Housner, 1959) and are suitable for evaluating long-period ground motions (e.g., Miyake and Koketsu, 2005).

MIEH09 is a rock-site station and is situated closest to the hypocenter and adjacent to the landward boundary of the accretionary wedge. At MIEH09, the synthetic waveforms of the models with the accretionary wedge (models A and B) have longer durations than the model without the accretionary wedge (model C). Although models A and B underestimate the total duration of the observed waveforms to some extent, they show better reproduction of the observed waveforms than model C. At WKYH08 and MIEH08, which are rock-site stations just outside the Osaka and Nobi basins, respectively, the synthesized waveforms of models A and B, especially in the north–south and up–down components, show a distinct wavetrain at a lapse time of 60–100 s, resulting in extended durations. This wavetrain also appears from 50 to 80 s in the waveforms of models A and B at MIEH09. However, because MIEH09 lies closer to the hypocenter than WKYH08 and MIEH08, the separation of this wavetrain from the direct wave is ambiguous. Meanwhile, the synthesized waveforms of model C at WKYH08 and MIEH08 also have later phases with large amplitudes at ∼60 s. As explained later, the wavetrain in models A and B can be understood as Rayleigh waves departing from the seaward edge of the accretionary wedge, whereas the later phases in model C do not stem from the existence of the accretionary wedge.

Station SZOH38 is located to the east of the accretionary wedge, and the observed features are recovered reasonably well by models A and B compared with model C. The amplitudes of the synthetics obtained by model A are slightly smaller than those of model B, even though those of model A at SZO018, a station inside the accretionary wedge, are larger than those of model B. This provides a good example demonstrating the higher impedance ratio at the accretionary wedge boundary in model A compared with model B, where most seismic energy is reflected back and the remainder is transmitted toward the outside of the accretionary wedge. As the largest foreshock occurred at a relatively shallow depth, large surface waves are also present in the waveforms of model C. These waves have a sharp peak relative to models A and B, probably owing to the absence of dispersion and trapping effects from the accretionary wedge. This peak results in larger velocity responses than those of models A and B (Fig. 5). At station TKY017, located in the Kanto basin, the synthetic waveforms of models A and B preserve their differences from model C as recognized at SZOH38, and their amplitudes are amplified. Although model C underestimates amplitudes in the latter part of the later phases, models A and B satisfactorily match the overall duration of observations. In model B, a conspicuous wavetrain is visible at 140–190 s, particularly in the east–west and up–down components, which corresponds to the wave after 140 s at SZOH38. This wave propagation is caused by efficiently transmitted waves from the eastern end of the accretionary wedge, as described in detail below.

We evaluated the total duration of long-period ground motions (Table 4) by measuring the elapsed time between 5% and 75% of the cumulative kinetic energy, as performed by Graves (2008). The cumulative kinetic energy is a
Figure 4. Velocity waveforms (0.05–0.3 Hz) at the stations marked in Figure 3a during the largest foreshock of the 2004 off the Kii Peninsula earthquake. Left, middle, and right columns denote east–west, north–south, and up–down components, respectively. Waveforms are shown only in the time window between the start and end of observed records, not from the earthquake origin time. Thus, the lapse time of 0 s at each station is systematically behind the earthquake origin time. The number on the right side of each waveform represents the peak amplitude. For each component, the observations and the synthetics of models A, B, and C are arranged in order from the top to the bottom. The amplitude of each waveform is normalized to the maximum amplitude of the observed and three synthetic waveforms. The blow line above each observed waveform denotes the time window of the direct wave.
parameter that takes into account the amplitude and duration of total motions (e.g., Olsen et al., 1995). The cumulative kinetic energy was obtained by integrating the square of the velocity amplitude of all three components over time and multiplying by half of the density. At all stations, models A and B show longer durations than model C, although there is a little difference in degree. This means that later phases are amplified and elongated by the accretionary wedge.

Spatial Distribution of Developed Long-Period Ground Motions

For models A and B, the snapshots of the wave propagation at 30 s show an obvious strong excitation of long-period ground motions in the accretionary wedge (Fig. 6). The excitation in model C is weaker relative to that in models A and B. To evaluate the development of long-period ground motions caused by the accretionary wedge, we calculated the cumulative kinetic energy ratio of models A and B to model C (Fig. 7). The cumulative kinetic energy was calculated in the same manner as the analysis of Table 4. For example, values of 2 and 0.5 mean that the energy of model A or B is twice and half as much as that of model C, respectively.

It is apparent that long-period ground motions are developed in the accretionary wedge. For model A, long-period ground motions show enhancement throughout the accretionary wedge, because the accretionary wedge is composed of a single layer with an $S$-wave velocity of 1.0 km/s. An abrupt change in the geometry at the landward edge of the accretionary wedge allows a large amount of energy to stagnate there; as a result, only a portion of the energy leaks outward. This causes a drastic energy drop across the landward boundary of the accretionary wedge. The most drastic energy drop is observable at the landward boundary in the Tonankai region for both models A and B, which reflects the most abrupt change in the total thickness of the accretionary wedge (Fig. 2). For model B, the strong excitation of long-period ground motions with a maximum energy ratio greater than 20 is concentrated on the Tonankai region, a narrow area in comparison with model A. As mentioned earlier, this region is characterized by thick and extremely low-velocity sediments, that is, the Kumano forearc basin. The extremely high value of the energy ratio suggests that long-period ground motions are significantly enhanced by the Kumano forearc basin.

Snapshots of models A and B at 115 s (Fig. 6) also demonstrate that long-period ground motions in velocity structure models with the accretionary wedge are considerably amplified at the landward edge of the accretionary wedge for model A and mainly in the Tonankai region for model B. The amplification in model A is due to the superposition of incident and reflected waves at the steep interface formed by the landward edge of the accretionary wedge. The amplification in model B is associated with the amplification effect of the Kumano forearc basin.

Notable Surface Waves along a Linear Profile from Offshore to Onshore

At 65 s after the earthquake origin time (Fig. 6), a wave propagation approaching the coastline area with a direction almost perpendicular to the seaward boundary of the accretionary wedge was detected, especially in model A. Our snapshots indicate that this propagation is probably responsible for the amplified and elongated later phases at the land area, although only a minority of its energy escapes from the accretionary wedge.

To investigate this propagation, we analyzed synthetic waveforms along a linear profile from the epicenter to the Osaka basin (Fig. 8a), which is aligned nearly perpendicular to both the seaward and landward boundary of the accretionary wedge. The radial waveforms of models A and B reveal a distinctive propagation of later phases behind $S$-waves in the accretionary wedge. As depicted in the cross-sectional views.
of velocity structure models (Fig. 8b), the hypocenter lies under a site where low-velocity sediments forming the accretionary wedge initiate thickening similar to that of a basin edge. If we regard the accretionary wedge as a basin, such later phases can be interpreted to be a type of basin-induced Rayleigh wave (e.g., Kawase, 2003), which are generated at the seaward edge of the accretionary wedge. These waves correspond to wavetrains at stations WKYH08 and MIEH08.

**Figure 6.** The horizontal ground velocity at 30, 65, 115, 175, and 240 s following the earthquake origin time of the largest foreshock of the 2004 off the Kii Peninsula earthquake. The snapshots were obtained by calculating the root mean square at every 1 s and multiplying by the hypocentral distance so that the geometric attenuation for body waves is compensated. Left, middle, and right columns display the results for models A, B, and C, respectively. Stars denote the epicenter. In the figures for models A and B, the areas enclosed by curves denote the accretionary wedge. The arrows and dashed areas indicate the important propagations from offshore to onshore. The color version of this figure is available only in the electronic edition.
The color enclosed by curves denote the accretionary wedge. Note that the highest energies are within the accretionary wedge. The areas developed by Saito (1988). According to the group velocity, these curves were calculated using the computer program 1D velocity structure models at 45 km along the profile. The snapshot of model B at 175 and 240 s (Fig. 6) clearly shows a wave propagation traveling northeastward from the eastern end of the accretionary wedge. This propagation serves to augment long-period ground motions in the Kanto basin, resulting in the conspicuous wavetrain at stations SZOH38 and TKY017 in model B (Fig. 4). We can interpret this propagation as a contributor to the guidance effect suggested by Furumura et al. (2008). In contrast, in model A, such propagation is not clear because the surface waves remain trapped by the accretionary wedge.

Cross-sectional views of transverse motions at 175 s along the linear profile toward the Kanto basin in models A and B (Fig. 9) confirm this difference between the two models. These views are separated into two period ranges, 3.3–10 and 10–20 s. For model A, a significant amplitude decline occurs at the interface between the accretionary wedge and the surrounding upper crust layers in both period ranges because of a dramatic velocity jump: the $S$-wave velocity of the former is 1.0 km/s, and that of the latter is 3.2 and 3.4 km/s. For model B, surface waves travel through the eastern part of the accretionary wedge, retaining large amplitudes. As shown at a distance of 180–260 km, the amplitude in the period range 10–20 s is larger than that in 3.3–10 s. The large amplitude at 10–20 s also extends to a greater depth than that of the bottom of the accretionary wedge. These findings imply that such surface waves are rich in the longer-period component and are hardly captured by the accretionary wedge. As illustrated in Figure 9, a layer with an $S$-wave velocity of 2.2 km/s predominantly fills the accretionary wedge at this area in model B. Hence, it is reasonable to deduce that hard sediments with $S$-wave velocities of $\sim$2 km/s play a role in trapping only shorter-period waves and efficiently transmitting longer-period ones. Moreover, as can be seen at $\sim$250 km (Fig. 9), the eastern end of the accretionary wedge is composed of only the layer with an $S$-wave velocity of 2.2 km/s, resulting in a lower impedance ratio. As a result, surface waves propagate outward, retaining large amplitudes, and thereby causing the gentler energy reduction in model B compared with model A at the eastern end of the accretionary wedge (Fig. 7). Our cross-sectional profiles for model B emphasize that the existence of the hard-sediment layer should be essential for the guidance effect toward the east of the accretionary wedge.

Accretionary Wedge Effects for Seismic Sources at the Plate Boundary

Although the largest foreshock of the 2004 off the Kii Peninsula earthquake was an intraplate event, great subduction earthquakes occur at shallower depths. Hence, we additionally simulated long-period ground motions originating from an interplate finite-source model ($M_w$ 7.4).

Figure 7. The cumulative kinetic energy of (a) models A and (b) B with respect to model C. Stars mark the epicenter of the largest foreshock of the 2004 off the Kii Peninsula earthquake. The areas as described previously (Fig. 4). We can also detect a progression of Rayleigh waves from a distance of $\sim$100 km in model C. Obviously, the Rayleigh waves in model C do not stem from the existence of the accretionary wedge and their travel times are earlier than those of models A and B. In the transverse component, although basin-induced Love waves generated at the seaward edge of the accretionary wedge are not visible, a low-velocity propagation of later phases emerges at a distance of 40–80 km and a lapse time of 50–110 s in model A. Figure 8c shows dispersion curves of the group velocity for Love waves in models A and B, using 1D velocity structure models at 45 km along the profile. These curves were calculated using the computer program developed by Saito (1988). According to the group velocity, the low-velocity propagation can be explained by Airy phases with group velocities of $\sim$0.6 km/s only in model A.

Sugioka et al. (2012) analyzed long-period ground motions at a frequency band of 0.07–0.17 Hz during very low-frequency events that occurred in the Tonankai region, using observed seismograms at ocean bottom sites inside the accretionary wedge and land sites. They showed evidence that prominent surface waves excited in the accretionary wedge such as Airy phases can significantly leak out of the wedge and propagate toward the land area. Although records obtained by ocean bottom seismometers were not available at the time of the largest foreshock of the 2004 off the Kii Peninsula earthquake, the simulation results of models A and B lead us to speculate that the amplified and elongated later phases observable at the land area are attributed to strongly developed surface waves that are associated with the accretionary wedge, such as basin-induced waves generated at the seaward edge of the accretionary wedge and Airy phases.

Control of Offshore–Onshore Propagation by Hard Sediments

For model A, the amplitudes of long-period ground motions in the accretionary wedge are maintained at a high level over a long time, as illustrated in the snapshots at 175 and 240 s (Fig. 6), because of the multiple reverberations resulting from the high impedance ratio formed by the layer with an $S$-wave velocity of 1.0 km/s and the surrounding upper crust layers. This notable feature is not visible in model B. The snapshot of model B at 175 and 240 s (Fig. 6) clearly shows a wave propagation traveling northeastward from the eastern end of the accretionary wedge. This propagation serves to augment long-period ground motions in the Kanto basin, resulting in the conspicuous wavetrain at stations SZOH38 and TKY017 in model B (Fig. 4). We can interpret this propagation as a contributor to the guidance effect suggested by Furumura et al. (2008). In contrast, in model A, such propagation is not clear because the surface waves remain trapped by the accretionary wedge.
Figure 8.  (a) Velocity waveforms (0.05–0.3 Hz) along a linear profile from the source to the Osaka basin during the largest foreshock of the 2004 off the Kii Peninsula earthquake. A map showing the basin is provided at the upper left. Thick line, star, thin curve, and triangles represent the profile location, epicenter, accretionary wedge, and K-NET and KiK-net stations, respectively. The leftmost column shows the observed waveforms at stations shown in the map. The other three columns show synthetic waveforms of models A, B, and C, at intervals of 5 km along the profile. The upper and lower rows are radial and transverse waveforms, respectively. Note that at the ocean area, waveforms at the seafloor are shown. The number on the right side of each waveform denotes the peak amplitude. Each waveform is multiplied by the hypocentral distance and normalized to the maximum amplitude of all waveforms. (b) Cross-section views of the velocity structure in models A, B, and C along the profile. Stars denote the hypocenter. Low velocities are observed within the accretionary wedge on the upper left and the Osaka basin on the upper right. Note that these views are vertically exaggerated. (c) Dispersion curves of the group velocity for Love waves in models A (solid line) and B (dashed line) calculated using 1D velocity structure models at 45 km along the profile. The color version of this figure is available only in the electronic edition.
A Virtual Finite-Source Model

With reference to the locations of strong-motion generation areas proposed by the Cabinet Office of Japan (2012), we located a finite-source model off the Kii Peninsula (Fig. 10a). The source model off the Kii Peninsula was selected because it is the shallowest of the source locations estimated by the Cabinet Office of Japan (2012) and can, thus, potentially yield the largest long-period ground motions. The size of the source model was $30 \text{ km} \times 30 \text{ km}$. The discretization in space was accomplished by dividing the fault plane into $\sim 1520$ subfaults, each 800 m long and 800 m wide. To prevent supershear rupture in the oceanic crust layer 2 (oceanic upper crust; Table 2), the depth of each subfault was set to a depth of 1 km shallower than the top of the oceanic crust in the velocity structure models (Kagawa et al., 2012). The entire source model had depths of 9–15 km. A triangular source time function with a pulse width of 0.5 s was assigned to represent the rupture slip on each subfault.Strike, dip, and rake angles on each subfault were based on Loveless and Meade (2010) and the Cabinet Office of Japan (2012). To overcome the excessive amplitudes expected in the direction of the rupture propagation, a random fluctuation of $\pm 30^\circ$ (the Cabinet Office of Japan, 2012) was introduced into the rake
We assumed that the rupture propagates to the north-northeast rather than the west-northwest because the former direction can generate larger long-period ground motions in the Osaka, Nobi, and Kanto basins. The rupture was assumed to propagate with a homogeneous velocity of $2.55 \text{ km/s}$, which corresponds to 75% of the S-wave velocity at the source region. The amount of slip was set to be 4.5 m, based on Kagawa et al. (2012) and Murotani et al. (2015), without heterogeneity. The simulation models covered an area of 783 km × 270 km (Fig. 10b) and extended to a depth of 69 km and an altitude of 1.8 km. The volume was discretized in the same manner as the simulations of the largest foreshock of the 2004 off the Kii Peninsula earthquake. Using the velocity structure models A, B, and C, we simulated the velocity waveforms during the 400 s after rupture initiation and band-pass filtered them at 0.05–0.3 Hz.

Accretionary Wedge Effects Depending on Source Location

We found that long-period ground motions in the land area show significant differences from the largest foreshock.
of the 2004 off the Kii Peninsula earthquake (Fig. 11). At sites WKYH08, OSKH02, MIEH08, and MIE003, the velocity responses of models A and B have a slightly lower level than those of model C at almost all periods; in contrast, there are no pronounced differences between three models during the largest foreshock (Fig. 5). The spectra at SZOH38 and TKY017 reveal that the velocity responses of models A and B are substantially decreased by the accretionary wedge relative to the case of the largest foreshock. At all sites, the peak amplitudes in the waveforms of model A and B also exhibit a decrease.

Furthermore, at WKYH08, OSKH02, MIEH08, and MIE003, waveforms of models A and B have no prominent later phases compared with that of model C. This feature could not be recovered for the largest foreshock of the 2004 off the Kii Peninsula earthquake, which occurred beneath the seaward edge of the accretionary wedge. Our finite-source model is positioned in the vicinity of the landward edge of the accretionary wedge, that is, close to the coastline area, and thus cannot give rise to a strong excitation of basin-induced surface waves at the seaward edge (Fig. 8), which can cause the amplification and elongation of later phases at the land area. Comparison between these two events leads us to believe that the accretionary wedge effect of amplifying and elongating later phases is restricted to the case of a seismic source at the seaward edge of the accretionary wedge, that is, near the trough axis. This suggestion is consistent with those of Shapiro et al. (1998) and Petukhin et al. (2016), who investigated the effects of the accretionary wedges along the Middle America trench and the Nankai trough, respectively.

During the largest foreshock of the 2004 off the Kii Peninsula earthquake, the efficient propagation of longer-period later phases from the accretionary wedge to the Kanto basin was conspicuous in model B, as marked by the dashed ellipse in Figure 9. However, the velocity waveforms and velocity response spectra at SZOH38 and TKY017 demonstrate that the difference in the longer-period component between models A and B is not as noticeable as for the finite-source model. For example, at SZOH38, the waveforms of model B at a lapse time of 150–250 s for the finite-source model are obviously rich in the longer-period component (Fig. 11), which also reflects the difference in the response spectra at periods of more than ∼10 s between models A and B; in contrast, differences in the waveforms between the two models during the largest foreshock (Fig. 4) are less significant than in the case of the finite-source model. Moreover, quantitative differences in the response spectra at all stations in the three models during the largest foreshock (Fig. 5) are not as remarkable as those for the finite-source model (Fig. 11). This is probably due to the difference in focal depth between the two events. For the finite-source model, because its depth is shallower than that of the largest foreshock (which was an intraplate event), most seismic waves directly enter the accretionary wedge. Therefore, of the quantitative differences in long-period ground motions generated in the offshore area, those resulting from variations of the velocity structure inside the accretionary wedge are the most dominant. In contrast, for the largest foreshock, most of the seismic waves reach the land area by traveling in crustal layers and without traveling through the accretionary wedge because of the large focal depth. The contribution of these waves only during the largest foreshock obfuscates the differences resulting from variations of the velocity structure inside the accretionary wedge, and thus causes the above differences between events. By comparing these two events, we suggest that focal depth is an important parameter in terms of enhancing/lessening accretionary wedge effects during offshore earthquakes along the Nankai trough.

Development of Longer-Period Waves from Offshore to Onshore

The velocity response spectra at SZOH38 show that the values in model B, where the layer with an S-wave velocity of 2.2 km/s is thick, are two or more times as much as those of model A in the period range beyond ∼10 s (Fig. 11). To clarify the mechanism of the enhancement of longer-period waves in model B, we analyzed the long-period ground motions in three period ranges, 3.3–5, 6–9, and 10–15 s, along a linear profile (Fig. 12). The waveforms at 10–15 s exhibit marked amplification at a distance of 60–140 km, where the Kumano forearc basin is the thickest (Fig. 12b). A secondary amplification can also be observed at 150–190 km, which roughly corresponds to the position of the eastern part of the Tonankai region. This area is called the Anoriguchi canyon, where the layer with an S-wave velocity of 1.2 km/s changes abruptly, forming a valley-like structure (Fig. 12b). Around the Anoriguchi canyon, some significant lateral variations in the velocity structure of the accretionary wedge, including this type of valley-like structure, were reported by Nakanishi, Shiobara, et al. (2002). We found that surface waves are highly scattered by an abrupt lateral variation associated with the Anoriguchi canyon. Consequently, the scattered surface waves contribute to the prolonged duration of long-period ground motions. A sequence of characteristic propagations as explained above is not prominent at 3.3–5 and 6–9 s. Furthermore, at ∼350 km, an impedance ratio lower than that of model A is effective in transmitting surface waves toward the outside of the accretionary wedge. Therefore, the resultant long-period ground motions have large amplitudes, long durations, and a higher longer-period component, as can be seen in the waveforms and spectra of SZOH38 and TKY017 (Fig. 11). Figure 12c shows velocity response spectra with a damping factor of 5%. At a distance above ∼350 km, which corresponds to the outside of the accretionary wedge, the velocity responses at periods of more than ∼10 s show high values compared with those of periods less than 10 s. This again supports the suggestion that hard sediments in model B have a critical effect in facilitating the efficient propagation of longer-period waves (Fig. 9).
Discussion

Evaluation Using Point Sources over the Nankai Trough

Our simulations for the largest foreshock of the 2004 off the Kii Peninsula earthquake and the finite-source model off the Kii Peninsula demonstrated that the source location controls accretionary wedge effects on long-period ground motions. To investigate the variation of accretionary wedge effects from the spatial source location, we also simulated long-period ground motions for point sources over the Nankai trough, as performed by Petukhin et al. (2016).

We deployed numerous point sources at intervals of ~10 km to cover the source region of subduction earthquakes along the Nankai trough (Fig. 13). We did not include deep point sources outside the accretionary wedge, because long-period ground motions from deep sources are hardly influenced by the accretionary wedge. The depth of each point source was also set to 1 km shallower than the top of the oceanic crust in velocity structure models, based on Kagawa et al. (2012). Shallow sources penetrating inside the accretionary wedge were also excluded on the basis that coseismic slips in soft sediments determine the size of tsunamis, not the intensity of ground motions (e.g., Park et al., 2002). Consequently, the total number of point sources was 596, with source depths of 5–26 km. Each point source was modeled to release a unit slip with a bell-shaped source time function with a rise time of 6 s. The assumptions of source

Figure 12. (a) Transverse velocity waveforms of model B at three period ranges (left) 3.3–5 s, (middle) 6–9 s, and (right) 10–15 s at intervals of 10 km along a linear profile from the source region to the Kanto basin. Note that waveforms at the seafloor are shown in the ocean area. In the leftmost map, the thick line, star, and thin curve represent the profile location, rupture initiation point, and accretionary wedge, respectively. The number on the right side of each waveform denotes the peak amplitude. Each waveform is multiplied by the hypocentral distance and normalized to the maximum amplitude of all waveforms. (b) Cross-sectional views of the velocity structure in model B along the profile. Star marks the rupture initiation point. Low velocities are observed within the accretionary wedge on the upper left and the Kanto basin on the upper right. Note that this view is vertically exaggerated. (c) Velocity response spectra with a damping factor of 5% for the transverse component in model B. The highest values are observed on the lower left and the lowest values on the lower right. The color version of this figure is available only in the electronic edition.
parameters and rise time were based on source models estimated by Loveless and Meade (2010) and the Cabinet Office of Japan (2012). Our simulation models (Fig. 13) were the same as those used for the finite-source model. The velocity structure models A, B, and C were also used for simulations. We simulated velocity waveforms at six sites identical to those in Figure 10b. Velocity waveforms were calculated with time durations of 400 s and were band-pass filtered at 0.05–0.3 Hz. To reduce computational time, a source–receiver reciprocity for seismic wavefields was jointly utilized with simulations, following Graves and Wald (2001) and Petukhin et al. (2016). We evaluated the simulated velocity responses at two period ranges: 5–7 and 10–13 s for sites WKYH08, OSKH02, MIEH08, and MIE003; and 7–10 and 10–13 s for sites SZOH38 and TKY017. The period ranges 5–7 and 7–10 s correspond to the resonance periods of the Osaka and Nobi basins and the Kanto basin, respectively (e.g., Miyake and Koketsu, 2005). The period range 10–13 s was evaluated to confirm the difference between models A and B. To discuss only accretionary wedge effects and avoid confusion with site amplification effects in basins, the velocity response ratios of models A and B to model C only at rock sites WKYH08, MIEH08, and SZOH38 are presented in Figure 13. Those at basin sites OSKH02, MIE003, and TKY017 are provided in Figure A1.

Figure 13. Maps of ratios of horizontal velocity responses with a damping factor of 5% of models A and B to model C at two period ranges, 5–7 and 10–13 s for sites WKYH08 and MIEH08, and 7–10 and 10–13 s for site SZOH38 derived from point sources over the Nankai trough. The results for sites OSKH02, MIE003, and TKY017 are illustrated in Figure A1. The value over a given period range was calculated by averaging the horizontal velocity response every 0.1 s, and the horizontal velocity response at each period was calculated by taking the maximum of the vector sum of the velocity response amplitudes for two horizontal components. In the leftmost map, the rectangular area, black curve, and triangles represent the simulation area, accretionary wedge, and target sites, respectively. The simulated point sources are shown corresponding to the source depth. The velocity waveforms for the three sources indicated by Q, R, and S are illustrated in Figures 14 and A2. In the maps of velocity response ratios, the areas enclosed by curves also denote the accretionary wedge. The color version of this figure is available only in the electronic edition.
supports our suggestions for the finite-source model. Recall that the finite-source model was positioned near the landward edge of the accretionary wedge (Fig. 10a). This source location led to small differences in velocity responses between the three velocity structure models at these sites (Fig. 11). At SZOH38, the velocity responses of model A at both 7–10 and 10–13 s are less than those of model C except for sources with short epicentral distances. Those of model B at the two period ranges indicate an increase for shallow sources. In particular, the increase at 10–13 s, where several sources exhibit a level that nearly equals or even surpasses that of model C, is more remarkable than at 7–10 s. This feature is in good agreement with that of the finite-source model (Fig. 11). The highest ratio of model B to model C at 10–13 s reaches nearly as high as three (Fig. 13).

Figure 13 revealed differences, particularly for shallow sources. To detail such differences, Figure 14 illustrates examples of velocity waveforms at rock sites provided by the three shallow sources shown in Figure 13. Those at basin sites are provided in Figure A2. The location of source Q corresponds to that of the largest coseismic slip during the 1946 $M_w$ 8.4 Nankai earthquake, as estimated by Murotani et al. (2015). Source R is the closest to the largest foreshock of the 2004 off the Kii Peninsula earthquake. Source S is located at the shallowest part of a strong-motion generation area in the Tokai region, as proposed by the Cabinet Office of Japan (2012). The depths of sources Q, R, and S are 9, 6, and 10 km, respectively. For source Q, the direct waves in model A exhibit a substantial amplitude decay because they are captured by the thick accretionary wedge layer with an $S$-wave velocity of 1.0 km/s. At SZOH38, prominent later phases can be detected in model B. These phases could be attributed to a sequence of amplifications by layers with $S$-wave velocities of 0.6 and 1.2 km/s and efficient propagation by the layer with an $S$-wave velocity of 2.2 km/s. For source R, the peak amplitudes of direct waves in models A and B largely decreased. Unlike source R, the direct waves in models A and B for the largest foreshock did not show a noticeable reduction relative to model C (Fig. 4). As detailed earlier, this difference is attributed to the source depth: for a depth of 6 km in source R, the depth of the largest foreshock is 18 km. At MIEH08, a conspicuous wavetrain is detected at a lapse time of ~130 s in model A. This feature may represent basin-induced surface waves excited at the seaward edge of the accretionary wedge and Airy phases that leak largely toward the land area, as discussed previously (Figs. 6 and 8). For source S, because seismic waves travel short distances inside the accretionary wedge, the development of later phases in models A and B associated with the accretionary wedge is less significant than that for sources Q and R.
Accretionary Wedge Effects Affecting Distant Sedimentary Basins

In distant sedimentary basins, long-period ground motions are influenced by both accretionary wedge effects and site amplification effects. We can discuss the degree of contribution of each effect to long-period ground motions by comparing basin-site and nearby rock-site stations.

We describe the case of the largest foreshock of the 2004 off the Kii Peninsula earthquake. At OSKH02 and MIE003, located in the central portion of the Osaka and Nobi basins, respectively, synthetic waveforms indicate that site amplification effects in basins slightly contaminate the difference in later phases between the presence and absence of the accretionary wedge observed at rock-site stations WKYH08 and MIEH08 (Fig. 4). Nevertheless, long-period ground motions of models A and B in basin-site stations show long total durations that exceed those of model C, just like rock-site stations (Table 4). This suggests that although site amplification effects affect later phases more critically than accretionary wedge effects, the accretionary wedge also plays an important role in transmitting seismic energy to distant sedimentary basins. At TKY017, in the Kanto basin, there was a loss in velocity responses of models A and B mainly in the period range of less than ~7 s (Fig. 5), which was caused by the accretionary wedge. Such loss was also observable at rock-site station SZOH38. Yoshimoto and Takemura (2014) compared long-period ground motions observed in the Kanto basin during the mainshock with other earthquakes, and demonstrated that the long-period ground motions during the mainshock lack the shorter-period component. Although the event that we simulated is the largest foreshock, comparison of models A and B with model C at SZOH38 and TKY017 supports the suggestion of Yoshimoto and Takemura (2014). This comparison also emphasizes the fact that the accretionary wedge has no minor influence on long-period ground motions that are not compensated for by site amplification effects.

Similar features of later phases and velocity responses common to both basin- and rock-site stations can be easily recognized for the finite-source model off the Kii Peninsula and the point sources that we simulated (Figs. 11, 13, 14, A1, and A2). These results mean that accretionary wedge effects should not be ignored in order to obtain accurate predictions of long-period ground motions during subduction earthquakes along the Nankai trough. The importance of interactions between multiple sedimentary basins in southern California was demonstrated by Olsen et al. (2006). Our simulations showed that for the Nankai trough, the accretionary wedge with low velocity also acts like a basin and affects long-period ground motions in the Osaka, Nobi, and Kanto basins.

Future Refinements of Velocity Structure Models of the Accretionary Wedge

To validate two velocity structure models with the accretionary wedge, we collected seismograms recorded by 491 K-NET, KiK-net, and SK-net (Takano et al., 2005) stations during the largest foreshock of the 2004 off the Kii Peninsula earthquake, and calculated the peak ground velocities (0.05–0.3 Hz) for the horizontal components (Fig. 15). Although model A overestimates values at the Kii Peninsula, and underestimates those just outside the eastern end of the accretionary wedge, it agrees well with observations at other sites. For model B, the fit between observed and simulated values is better than model A.

Model B apparently achieves better reproduction of observations than model A; however, in terms of the duration of long-period ground motions, it is difficult to assess the superiority of one model over the other. For example, both models A and B underestimate the durations of observations by ~30% at MIEH09 and WKYH08 (Table 4), probably because well-scattered surface waves might not have been sufficiently reproduced. A comparison between cross-sectional views of velocity structure models in Figures 8b and 12b shows that in the accretionary wedge, the former does not show lateral variation. As illustrated in Figure 12a, the scattering of surface waves can be caused by the existence of significant lateral variations in velocity structure, such as the Anoriguchi canyon. This comparison leads us to surmise that a velocity structure model with sufficient structural heterogeneity, for example, lateral variations, should be required around the profile in Figure 8 to explain the scattered surface waves and observed long durations. In the Tonankai region, a mega-splay fault system and the associated heterogeneity in seismic velocity were identified in the deep portion of the accretionary wedge (e.g., Kamei et al., 2012). This heterogeneity may be a factor elongating long-period ground motions because of the scattering effect, although models A and B did not include it.

Existing velocity structure models have high uncertainty at two zones (e.g., Kodaira et al., 2000; Takahashi et al., 2002). One is the bottom of the accretionary wedge. As mentioned earlier, the S-wave velocity of hard sediments in model B, which constitute the bottom of the accretionary wedge, was defined as 2.2 km/s on the basis of the Poisson’s ratio. The hard sediments are critical for facilitating the propagation of long-period ground motions from offshore to onshore. The uncertainty of accretionary wedge effects resulting from the S-wave velocity of hard sediments should be more carefully investigated as a future task. The other zone is the interface between the accretionary wedge and upper crust near the coastline area. The real accretionary wedge might extend to the interior of the Kii Peninsula and have a more gradual interface with the upper crust, whereas the interface in models A and B was along the coastline and not located on the Kii Peninsula. As models A and B had the same accretionary wedge geometry and differed only in seismic velocity, we could not consider the possibility of the landward extension of the accretionary wedge. Evaluation of the variations of long-period ground motions caused by this landward extension requires further study.

The S-wave velocity in the upper crust can indirectly influence the amplification of long-period ground motions. At
SZ0018, the observed waveforms are successfully explained by model A, whereas model B yields synthetics with small amplitudes (Fig. 4). Tsuno and Kudo (2008) proposed an S-wave velocity structure model beneath this area, in which sedimentary layers with S-wave velocities of 1–2 km/s reach a depth of 4–5 km, overlying an upper crust layer with an anomalously high S-wave velocity of 4 km/s. They implied that this high-velocity contrast is essential for contributing to substantial long-period ground motions in this area. Model A is better in terms of incorporating such contrast (Fig. 2a and Table 2), although the S-wave velocities in sediments and the upper crust are slightly lower than those of Tsuno and Kudo (2008). Thus, further discussions about accretionary wedge effects from the perspective of the interaction of the accretionary wedge with the surrounding upper crust are necessary.

Because the validations of models A and B were limited to land stations (Table 4 and Fig. 15), it is still difficult to assess directly the performances of the two models. For further validation and improvement of the velocity structure models of the accretionary wedge, ocean bottom seismometers installed inside the accretionary wedge should be utilized. For the Nankai trough, although the poor coverage of ocean bottom seismometers and the low seismic activity in the offshore area make validation of velocity structure models difficult, data from the Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) (e.g., Kaneda et al., 2009) in the Tonankai region have recently become available. Furthermore, long-period ground motions up to 0.5 Hz can severely damage high-rise buildings at the land area (e.g., Beck and Hall, 1986). However, the upper limit of the frequency band used in our simulations was 0.3 Hz because of our computational limitations. Nakamura et al. (2014) also implied that velocity structure models in the offshore area have relatively low accuracy at >0.2 Hz, which is due to the lower resolution than the onshore area. Therefore, as important future tasks, refinements using ocean bottom seismometers aimed at developing a detailed velocity structure model in the offshore area as well as long-period ground-motion simulations with finer meshes are required for predictions of long-period ground motions with sufficient accuracy.

Conclusions

To clarify the effects of the accretionary wedge along the Nankai trough on long-period ground motions, we performed long-period ground-motion simulations (0.05–0.3 Hz) for the largest foreshock of the 2004 off the Kii Peninsula intraplate earthquake (MW 7.2) and spatial seismic sources at the plate boundary. We used three 3D velocity structure models: two with different accretionary wedge models, and the other without the accretionary wedge to compare long-period ground motions with and without the accretionary wedge. Our simulation results demonstrated that the accretionary wedge has the effect of decreasing the peak amplitude and velocity re-
response but amplifying and elongating later phases of long-period ground motions in the land area. These effects depend significantly on the focal depth and are pronounced for shallow seismic sources. We detected several velocity structures of the accretionary wedge and the corresponding wave propagations associated with the amplification and elongation of later phases in the land area, which are summarized in Table 5. There are two important velocity structures and wave propagations. One is basin-induced velocity structures wave originating from the seaward edge of the accretionary wedge; the other is the hard-sediment layer in the accretionary wedge, which has intermediate S-wave velocity and facilitates the propagation of long-period ground motions from offshore to onshore. In the case of the Nankai trough, this layer allows long-period ground motions developed inside the accretionary wedge to be efficiently transmitted outward in the longer period than \( \sim 10 \) s. Long-period ground motions in distant sedimentary basins suggest that the effects of the accretionary wedge are not sufficiently small to be ignored relative to site amplification effects, which have a critical influence. For more accurate predictions of long-period ground motions for great earthquakes along the Nankai trough, velocity structure models of both the accretionary wedge and the surrounding upper crust should be validated and revised using seafloor observations.

### Data and Resources

The strong-motion data recorded by K-NET/KiK-net and SK-net stations were obtained from the National Research Institute for Earth Science and Disaster Prevention (NIED) at [http://www.kyoshin.bosai.go.jp/kyoshin/](http://www.kyoshin.bosai.go.jp/kyoshin/) (last accessed November 2015) and the Earthquake Research Institute, University of Tokyo at [http://www.sknet.eri.u-tokyo.ac.jp/](http://www.sknet.eri.u-tokyo.ac.jp/) (last accessed November 2015), respectively. The source information determined by Yuji Yagi (from the University of Tsukuba) and the Cabinet Office of Japan were obtained from [http://iiseseikenken.go.jp/staff/yagi/eq/Japan20040905/Japan20040905_1-j.html](http://iiseseikenken.go.jp/staff/yagi/eq/Japan20040905/Japan20040905_1-j.html) (last accessed November 2015) and [http://www.bousai.go.jp/jishin/nankai/model/index.html](http://www.bousai.go.jp/jishin/nankai/model/index.html) (last accessed November 2015), respectively. Figures are drawn using the Generic Mapping Tools version 4.5.5 ([http://www.soest.hawaii.edu/gmt/](http://www.soest.hawaii.edu/gmt/), last accessed November 2015; Wessel and Smith, 1998).

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### References


Appendix

Here we provide the results (Figs. A1 and A2) of long-period ground motions simulated at basin sites OSKH02, MIE003, and TKY017 for point sources over the Nankai trough. Although most point sources indicate that the velocity responses of both models A and B are less than those of model C, the velocity responses of model B at 10−13 s are roughly comparable to those of model C (Fig. A1). This again implies that hard sediments can enhance the efficient propagation of longer-period waves (Figs. 9 and 12). In other words, longer-period waves are scarcely trapped by the accretionary wedge owing to the existence of hard sediments.

Figure A1. Maps of ratios of horizontal velocity responses with a damping factor of 5% of models A and B to model C at two period ranges, 5−7 and 10−13 s for sites OSKH02 and MIE003, and 7−10 and 10−13 s for site TKY017 derived from point sources over the Nankai trough. The value over a given period range was calculated by averaging the horizontal velocity response every 0.1 s, and the horizontal velocity response at each period was calculated by taking the maximum of the vector sum of the velocity response amplitudes for two horizontal components. The areas enclosed by curves also denote the accretionary wedge. The color version of this figure is available only in the electronic edition.
Furthermore, the distribution patterns of the velocity response ratios of models A and B to model C at OSKH02, MIE003, and TKY017 are very similar to those at the nearby rock sites WKYH08, MIEH08, and SZOH38 (Fig. 13), respectively. In spite of the amplification and complication caused by site amplification effects in basins, the waveforms at OSKH02, MIE003, and TKY017 (Fig. A2) preserve important features included in WKYH08, MIEH08, and SZOH38, respectively, which are associated with accretionary wedge effects. For example, for source R, the conspicuous wavetrain detected at a lapse time of ∼150 s at MIE003 in model A is related to that at ∼130 s at MIEH08 (Fig. 14). These also emphasize the fact that accretionary wedge effects as well as site amplification effects significantly affect long-period ground motions in distant sedimentary basins.

Figure A2. Velocity waveforms (0.05–0.3 Hz) of models (top) A, (middle) B, and (bottom) C in the north–south component at sites OSKH02, MIE003, and TKY017 for three point sources. The amplitude of each waveform is normalized to the maximum amplitude of three waveforms. The number on the right side of each waveform denotes the peak amplitude.